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Using the Advanced Research Version of the Weather Research and Forecasting Model (WRF-ARW) to Forecast Turbulence at Small Scales

by Jeffrey E. Passner

ARL-TR-4575 **September 2008**

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14. ABSTRACT
The U.S. Army Research Laboratory (ARL) has an interest in high spatial and temporal resolution weather output with an emphasis on products that assist warfighter decision aids and applications in battlefield environments. This model study was done in support of the short-range Army tactical analysis/nowcasting system called the Weather Running Estimate-Nowcast (WRE-N) as well as for longer-range forecasting support. The model utilized to investigate fine-scale weather processes, the Advanced Research version of the Weather Research and Forecasting model (WRF-ARW), was run with a triple nest of 18-, 6-, and 2-km grids over a 24-h period. One of the long-term intriguing model areas of study is clear-air turbulence due to the effects of turbulence on Army Aviation aircraft and onboard sensors. This study investigates the WRF-ARW output over northeastern New Jersey during the winter season of 2006–2007. Using a combination of the Panofsky Index (PI) in the boundary layer and the Turbulence Index (TI) above the boundary layer, a small sample of 75 pilot reports was compared to “YES/NO” turbulence forecasts over the 24-h forecast period. Results were very encouraging using both the 18- and 2-km output, with a probability of detection over 0.70, although the testing was biased to days with a high probability of turbulence.

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Mesoscale, WRF, evaluation, turbulence

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Summary

The U.S. Army Research Laboratory (ARL) has an interest in high spatial and temporal resolution weather output. To accomplish the goal of fine-scale weather products, a model study was completed in support of the short-range Army tactical analysis/nowcasting system called the Weather Running Estimate-Nowcast (WRE-N). The model utilized to investigate fine-scale weather processes, the Advanced Research version of the Weather Research and Forecasting model (WRF-ARW), was run with a triple nest of 18-, 6-, and 2-km grids over a 24-h period. One of the long-term intriguing model areas of study is clear-air turbulence due to the effects of turbulence on Army Aviation aircraft and onboard sensors. This study investigates the WRF-ARW output and model skill as well as turbulence forecasts over northeastern New Jersey during the winter season of 2006–2007. Using a combination of the Panofsky Index (PI) in the boundary layer and the Turbulence Index (TI) above the boundary layer, a small sample of 75 pilot reports was compared to “YES/NO” turbulence forecasts over the 24-h forecast period. Results were very encouraging using both the 18- and 2-km output, with a probability of detection over 0.70, although the testing was biased to days with a high probability of turbulence. It should be noted that the 6-km WRF output was not evaluated in this study.

However, it was found on the 2-km grid that the forecasted intensity of turbulence was excessive in many cases. It became apparent that a variable such as turbulence would need to be parameterized at smaller scales.

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1. Introduction

The Battlefield Environment Division of the Computational and Information Sciences Directorate of the U.S. Army Research Laboratory (ARL) has an interest in high spatial and temporal resolution weather output with an emphasis on fine-resolution, short-range forecasts in complex terrain. The Advanced Research version of the Weather Research and Forecasting model (WRF-ARW) was run with a triple nest of 18-, 6-, and 2-km grids over a 24-h period. The main emphasis in the model runs was in the post-processed clear-air turbulence (CAT) since the effects of turbulence on Army Aviation aircraft and onboard sensors are vital to Army aviation. Using a combination of the Panofsky Index (PI) in the boundary layer and the Turbulence Index (TI) above the boundary layer this study investigates the WRF-ARW output over northeastern New Jersey during the winter of 2006–2007. A total of 75 pilot reports (PIREPs) were evaluated to compare against the derived turbulence forecasts.

Although the test was biased to days of a high probability of turbulence, results were encouraging using both the 18- and 2-km output, with a probability of detection over 0.70. It should be noted that the 6-km output was not evaluated in this study. However, it was discovered on the 2-km grid that the forecasted intensity of turbulence was excessive in many cases. There was no evident term in the TI that seemed to cause the problem; however, in many of these cases one or two terms were an order of magnitude higher at 2 km than at 18 km. One correction that was made to the software was an adjustment in parameterizing the turbulence to adjust for smaller scales.

2. The WRF

The WRF model is a next-generation mesoscale weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores and a software architecture allowing for computational parallelism and system extensibility. The WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. (*1*)

2.1 Model Configuration for ARL Study

The WRF runs for this model study were completed using WRF version 2.1.2. All the model runs used the WRF-ARW dynamical core and were initialized with 0000 universal time coordinates (UTC) 40-km WRF data. The models were run for a period of 24 h with model output available every hour. The NJ model runs used a three nest configuration of 18-, 6-, and 2-km grid resolutions with 43 vertical levels. The WRF model was run on the Army's High

Performance Computing Research Center Linux Network Evolocity II, which is a cluster system. (*2*)

The physics packages used for all model runs were the following:

- Lin Microphysics
- Rapid Radiative Transfer Model (RRTM) long-wave radiation
- Dudhia short-wave radiation
- Mesoscale Model Version 5 (MM5) similarity for surface-layer physics
- Noah Land Surface Model
- Yonsei University scheme for planetary boundary layer
- Kain-Fritsch cumulus parameterization for greater than 8-km grids only
- Four soil layers

3. NJ Model Runs and Evaluation

3.1 NJ Terrain

The evaluation of the WRF model was done at the Caldwell, NJ, airport (CDW). This site was selected since it is far enough away from the buildings of urban New York City yet it included more complex terrain, soil moisture influences, the complicated interaction of nearby water with the land mass, some urban heat influences, and available weather data for verification and validation. Caldwell is located at 40.87N and 74.28W with an elevation of 53 m.

A secondary reason for selecting this area to evaluate the WRF was that it is located close to several major airports, which provided an opportunity for more PIREPs and more chances for turbulence verification.

Figure 1. The complex terrain of the Caldwell, NJ, area.

Note: Source: http://maps.yahoo.com/#mvt=s&lat=40.87998&lon=-74.289624&zoom=15&q1=Fairfield%2C%20NJ%2C%2007004.

3.2 NJ WRF Performance and Evaluation

An evaluation of the basic model output was completed during the period July 2006 to March 2007 using 37 model runs at the CDW site. Table 1 shows the absolute temperature error, mean error, and correlation coefficient for the 18-km model output at all forecast hours through the entire 24-h forecast output. Table 2 shows the data for the 2-km output for the same time period.

Table 1. WRF results at CDW from July 2006 to Mar. 2007, 18-km resolution.

	Average Absolute Error	Mean Error	Correlation
Temperature (°C)	1.6	-0.1	0.99
Dew point (°C)	1.9	0.2	0.99
Wind direction (°)	22	6	0.80
Wind speed (knots)	1.0	0.3	0.77

Table 2. WRF results at CDW from July 2006 to Mar. 2007, 2-km resolution.

	Average Absolute Error	Mean Error	Correlation
Temperature (°C)	1.6	0.3	0.98
Dew point (°C)	1.8	0.4	0.97
Wind direction (°)	18	7	0.86
Wind speed (knots)	2.5	0.7	0.77

As shown in table 1, the WRF does show excellent skill and correlation for this location. However, this is not unexpected given the lack of complex weather situations and generally light wind speeds during much of the study.

The results in tables 1 and 2 show general agreement with only minor differences in the skill between the 18- and 2-km resolution output at the point tested. There are no strong biases noted in any of the parameters for the location tested.

4. Turbulence Evaluation

4.1 Turbulence

Forecasting CAT is a complicated problem because of the small timescale and resolution at which turbulence is often observed. Theoretical studies and empirical evidence have associated CAT with Kelvin-Helmholtz instabilities. Miles and Howard (*3*) indicate that the development of such instabilities require the existence of a critical Richardson number (RI) ≤0.25. Stull (*4*) notes that the RI is a simplified term or approximation of the turbulent kinetic energy equation where the RI is expressed as a ratio of the buoyancy resistance to energy available from the vertical shear.

The equation for the RI is expressed below:

$$RI = \frac{\frac{g}{\theta} * (\frac{\partial \theta}{\partial Z})}{(\frac{\partial V}{\partial Z})^2} \quad (1)$$

where g is the gravitational acceleration, $\frac{\partial \theta}{\partial Z}$ is the change of potential temperature with height, and ∂V is the vector wind shear occurring over the vertical distance ∂Z.

Numerous scientists have attempted to use both theoretical and observational data to formulate techniques to forecast CAT. Dutton and Panofsky (*5*) associated vertical shear instabilities with turbulence. Bacmeister et al. (*6*) noted an obvious correlation between mountain waves and turbulence. Keller (*7*) developed the "SCATR" index, which relates the nonturbulent component of the tendency of the RI to stretching deformation and shearing deformation. McCann (*8*) showed that correlation coefficients are rarely greater than ±0.35 when using the existing methods. These are just a small sample of studies conducted to forecast or predict CAT.

Boyle (*9*) of The U.S. Navy Fleet Numerical Meteorological and Oceanography Center (FNMOC) used the PI to forecast low-level turbulence, where the low level is considered to be below 4,000 ft above ground level (AGL). The formula for this index is as follows:

$$PI = (windspeed)^2 * (1.0 - RI/RI_{crit}) \quad (2)$$

where RI is the Richardson number and RI_{crit} is a critical Richardson number empirically found to be 10.0 for the FNMOC data. The higher the PI, the greater the intensity of turbulence at low levels.

Ellrod and Knapp (*10*) listed environments where significant CAT was found to be prevalent. Their study associated vertical wind shear (VWS), deformation (DEF), and convergence (CVG) into a single index as shown below in equation 3, which is called the TI.

$$TI = VWS * [DEF + CVG] \quad (3)$$

The DEF term is a combination of stretching deformation and shearing deformation.

Originally, of all the methods used to forecast turbulence using a single sounding, the RI seemed to make the most sense physically, since it included the influence of both the temperature and shear in the atmosphere. Based on the work of McCann (*8*), the RI also displayed the most skill of several methods tested. However, Passner (*11*) found in his study between 1995 and 1997 that the PI provided more skill than the RI in the lowest 4,000 ft AGL using upper-air observation data alone. Additionally, results showed that the RI was generally ineffective between 5,000 to 10,000 ft AGL, and although it was more effective above 10,000 ft AGL, it underforecasted turbulence at all levels. Knapp et al. (*12*) used Higher Order Turbulence Model for Atmospheric Circulations (HOTMAC) mesoscale model output in their study. HOTMAC was a very course model with only 22 vertical levels and 20-km grid spacing at that time. Knapp noted that the TI was based on the frotogensis equation and the results of his work indicated that DEF+CVG correlated best in the low levels, which implied that horizontal wind flow changes were more vital than vertical motion fields in determining turbulence in the low levels. Passner decided to combine the PI and TI for use in mesoscale model output and used the PI below 4,000 ft AGL and the TI above 4,000 ft AGL as the way to calculate turbulence from model output.

4.2 Turbulence Evaluation

The method used in this study to verify turbulence is to compare PIREPs to model forecasts. Using the WRF output, verification is limited to a 1-h period surrounding the model forecast time. As an example, model forecasts of turbulence at 2100 UTC are compared to PIREPs from 2030 to 2130 UTC only. Any PIREPs that included two intensities, such as light (LGT) to moderate (MOD), were classified as the more extreme intensity. As a standard, only PIREPs close in height to the model forecast were accepted. For levels below 10,000 ft AGL, the forecasted turbulence had to be within 1,000 ft of the PIREP. From 10,000 to 20,000 ft AGL, the forecast had to be within 1,500 ft of the PIREP, and above 20,000 ft AGL, the forecast had to be within 2,000 ft of the observed turbulence.

The turbulence evaluation was done between August 2006 and April 2007 using a small sample of about 75 PIREPs over the New Jersey-New York metropolitan area. This time frame included a variety of weather conditions and seasons. Table 3 shows the results of this study for both the 18- and 2-km grid resolutions, where POD is Probability of Detection, FAR is False Alarm Ratio, TSS is True Skill Score, and Bias is the bias to overforecast or underforecast an event. A value of over 1.0 is considered an “overforecast,” while a value of under 1.0 is an “underforecast” bias.

Table 3. Turbulence “YES/NO” forecast skill using WRF output for 24-h forecasts over NJ grid.

	18-km WRF	**2-km WRF**
POD	0.73	0.83
FAR	0.28	0.30
TSS	0.12	0.20
Bias	1.02	1.19

The results in table 3 are encouraging, using the WRF output and the combination of the TI above (4,000 ft AGL) and PI (below 4,000 ft AGL). However, a closer investigation of these data indicated that the lower levels, using the PI, had higher skill than the TI. Table 4 shows the skill associated with the TI over the NJ grid for both the 18- and 2-km WRF grids for points above 4,000 ft AGL.

Table 4. Turbulence “YES/NO” forecast skill above 4,000 ft using TI for WRF output for 24-h forecasts over NJ grid.

	18-km WRF	**2-km WRF**
POD	0.68	0.80
FAR	0.37	0.45
TSS	0.15	0.23
Bias	1.31	1.56

As can be seen in table 4, the FAR is higher using the TI only, which leads to a much higher bias. This indicates that the turbulence is being overforecasted significantly using the TI derived from the WRF output. It does appear that while the POD is higher for the 2-km TI study, the bias is even higher. It should be noted that there were only 45 samples used to derive these statistics; however, some additional studies over the NJ grid in 2008 also followed the trends seen in table 4.

In figures 2 and 3, the plots show the turbulence forecast for 1500 UTC 08 August 2006 over the NJ grid.

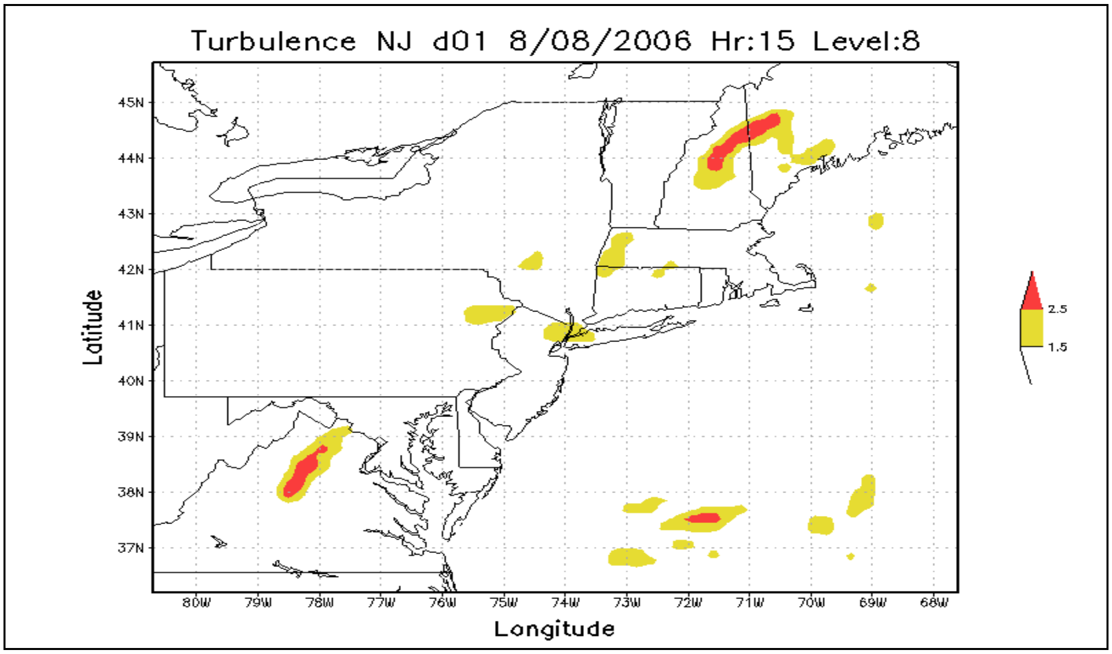

Figure 2. Turbulence forecast at 1500 UTC 08 Aug. 2006 using 18-km WRF output at 4,000 ft AGL.

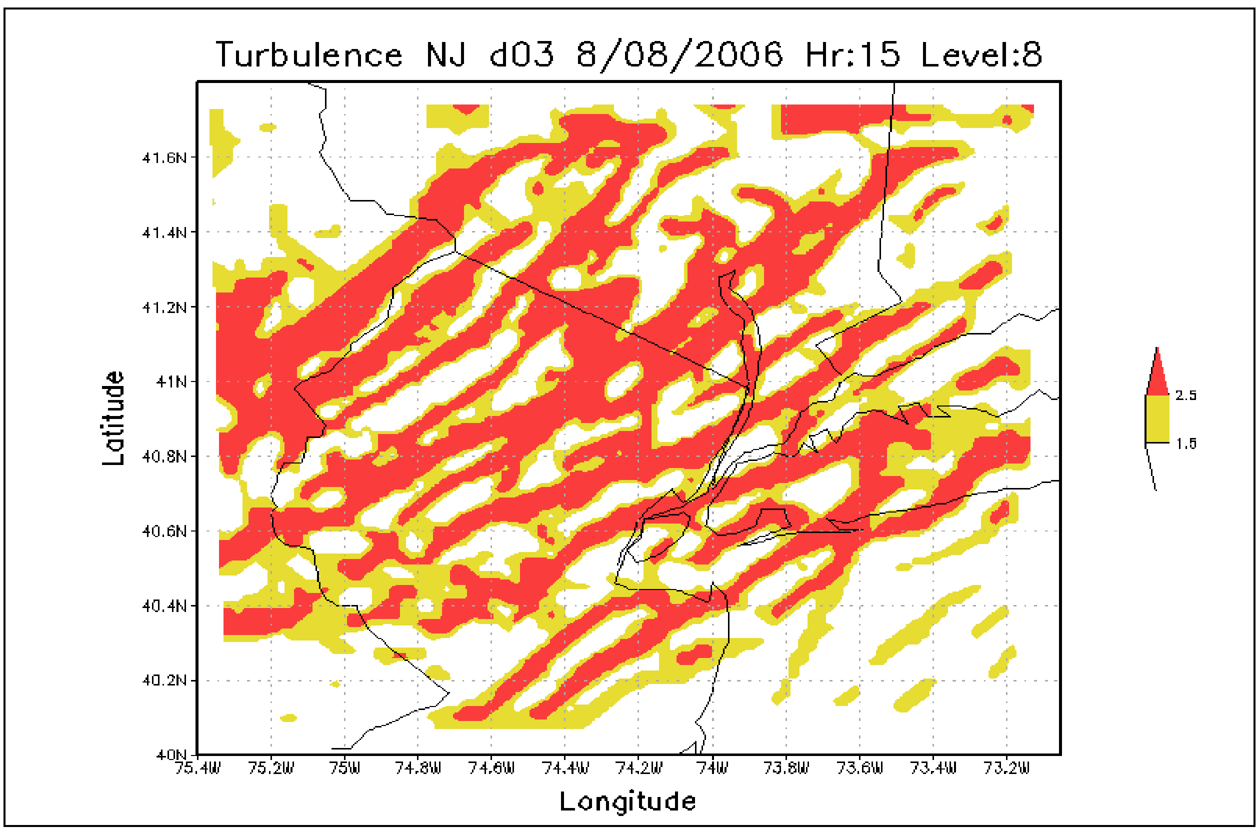

Figure 3. Turbulence forecast at 1500 UTC 08 Aug. 2006 using 2-km WRF output at 4,000 ft AGL.

In figure 2, the LGT turbulence or no turbulence is shown using the white shade, MOD turbulence is indicated with the yellow colors, and severe (SEV) turbulence is displayed in red. As can be seen in the plot, there is little turbulence noted over the grid except over the higher terrain of New Hampshire and Virginia. The same colors are shown in figure 3, which is a 2-km resolution model run also on 08 August 2006. As can be expected, the domain size is smaller, but the inner domain has a large coverage of moderate and severe turbulence.

Examining the two plots in figures 2 and 3, there are significant differences between the 18- and 2-km resolution data as there is far greater coverage of turbulence forecasted using the 2-km WRF output than the 18-km data, which agrees with the statistics shown in table 4. In general, these data for the entire experiment from August 2006 to April 2007 did show more intense and higher turbulence coverage at 2 km than at 18 km. For example, on the 18-km domain 40% of the forecasts were for MOD or SEV turbulence, while 43% of the observations on those days were for MOD or SEV turbulence. On the 2-km domain, 58% of the forecasts were for MOD or SEV turbulence, while 40% of the observations contained reports of MOD or SEV turbulence. Overall, using the 2-km output, 25 turbulence forecasts were for SEV turbulence but only 4 cases verified as SEV in the sample of 67 cases.

On the day in question, 08 August 2006, a small sample of PIREPs over the region indicated no turbulence except for some LGT chop or occasional LGT in the layer from 2,500 to 3,500 ft AGL. Based on the 1200 UTC upper-air observation at Upton, NY, airport (KOKX) as seen in figure 4, the winds were from 330° at 20 to 25 knots in this layer. There was some directional shear noted in the layer but little speed shear.

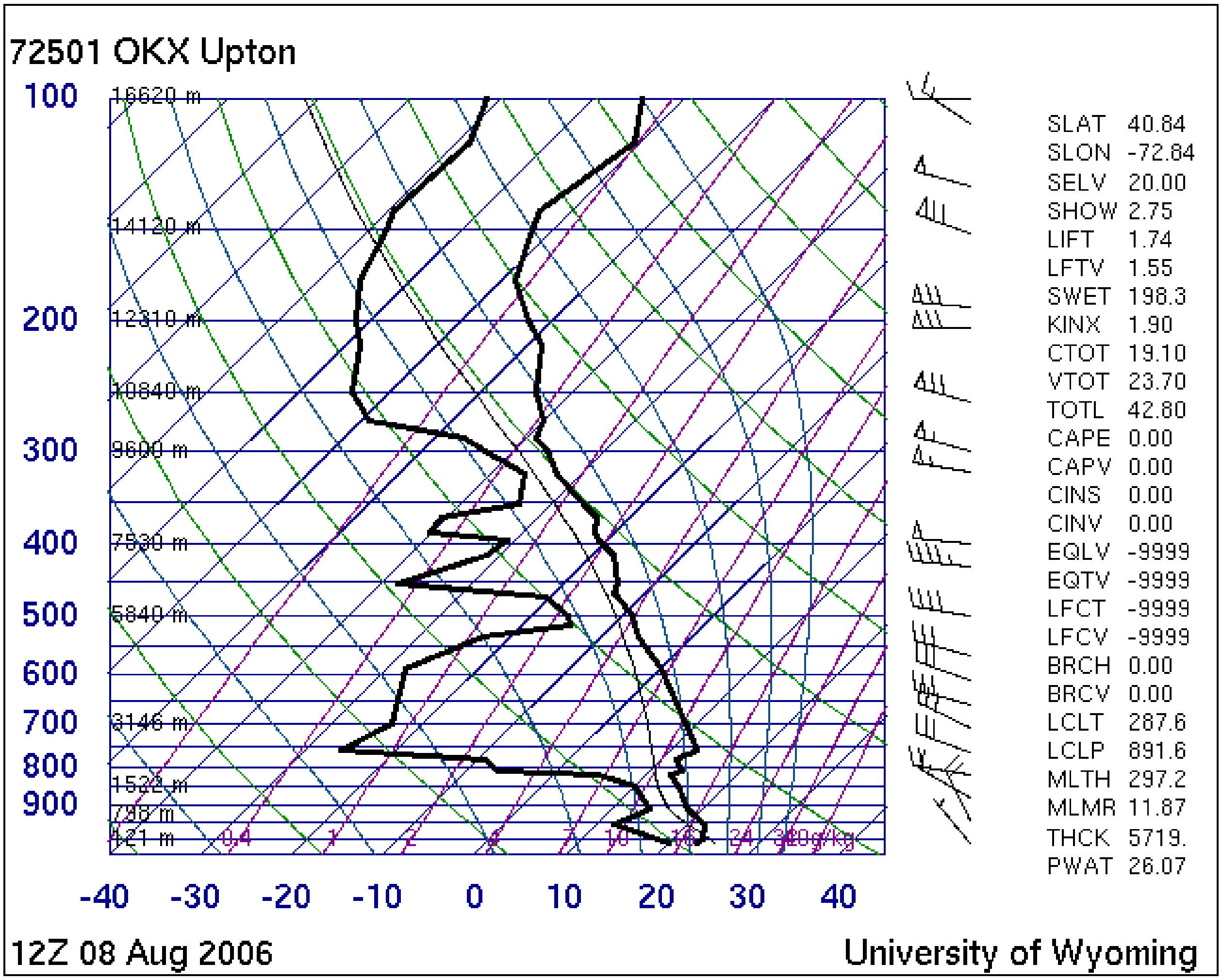

Figure 4. Upper-air observation from 1200 UTC 08 Aug. 2006.

Note: Source: http://weather.uwyo.edu/upperair/sounding.html

It becomes a question as to why the strong bias for overforecasting turbulence and turbulence intensity at the 2-km horizontal resolution occurs. A careful investigation of the TI equations at 9,500 ft AGL on 08 August 2006 shows that all terms of the TI were larger in the 2-km domain with the shearing term showing the largest difference. Most of the terms were about one order of magnitude larger with the shearing term two orders of magnitude larger. The turbulence forecast at 18-km was LGT while the forecast at 9,500 ft AGL on the 2-km grid was SEV at 1500 UTC. Based on a PIREP at 1452 UTC over the White Plains, NY, area at 8,500 ft AGL turbulence was reported as “negative.”

Several other cases such as the 01 December 2006 case show the shearing term to be as much as two orders of magnitude larger on the 2-km grid than the 18-km grid at 4,200 ft AGL. At a higher level of 5,100 ft AGL, this trend was still noted on the 01 December 2006 case. However, the tendency for just the shearing term to be an order or two magnitude higher was not noted

consistently, as the 14 February 2007 case indicated that the stretching, shearing, and deformation terms were all larger on the smaller domain. Additionally, the case of 05 March 2007 over the LaGuardia, NY, airport at 9,200 ft AGL showed a larger difference in the stretching and convergence terms. This led to a forecast of MOD turbulence on the 2-km grid and no turbulence on the 18-km grid.

Based on these calculations, it is apparent that the terms are scale dependent; thus, a smaller grid size results in larger growth in the main terms in the TI. Many of the spurious cases of SEV turbulence do appear to follow the terrain features; however, after careful study it is uncertain why this would be. Logically, the convergence of the wind field would be a cause, but the convergence term in the TI is mathematically the least significant term in the equation set. The vertical shear term did not show any significant difference between the 18- and 2-km grids. Further studies were done to find a point where the terms in the TI grew large enough to cause the increase in turbulence intensity. It was found that an about 8-km grid resolution acted as a cut-off between effective and ineffective resolution of turbulence. This work follows some of the logic of a cumulus parameterization, where grid size does greatly influence the result of the convective development. It can be argued that below a certain grid size that turbulence cannot or should not even be resolved. However, turbulence forecasts remain a very important forecasting issue and a smoothing or different approach at smaller scales is necessary.

4.3 Turbulence Evaluation for UAS Exercise

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) supported Joint Improvised Explosive Device Defeat Organization (JIEDDO)-funded unmanned aircraft flights in a specified airspace domain at Yuma Proving Ground (YPG), AZ, in November and December 2007. ARL was asked to provide real-time meteorological modeling support and turbulence forecasts. Additionally, one ARL meteorologist was sent to YPG during each exercise in order to provide on-scene support and interpretation of the model forecast output and products (*13*).

The exercises held at YPG focused on testing sensors and communications aboard the ScanEagle Unmanned Aerial System (UAS). During the YPG exercises, missions ranged from an hour to several hours duration. Due to the nature of the JIEDDO tests, the ScanEagle was required to fly within the first 60 m above ground. To resolve the majority of the local terrain features of mesoscale meteorological significance, a double-nested configuration was adopted by ARL for the WRF-ARW. The outer nest of 3-km grid spacing had a horizontal resolution of 171x171, resulting in an areal domain of 510 km x 510 km. The inner nest of 1 km grid spacing had a horizontal dimensionality of 73x73 grid points, resulting in an areal domain of 72 km x 72 km. In order to better resolve the lower levels, more sigma layers were placed in the lowest 1,000 ft AGL and the model runs were conducted with 60 vertical levels.

The 24-h forecast period commenced at 0000 UTC on the evening prior to a planned flight launch, and unlike much of the previous ARL work, the turbulence forecasts were derived using the PI rather than the TI for this test since the flights were all conducted near the surface. Results of the turbulence forecasts were very positive; however, some deficiencies were found in the forecasting techniques. Figure 5 show an example of a wind and turbulence forecast for a very small area over the YPG where flights were tested.

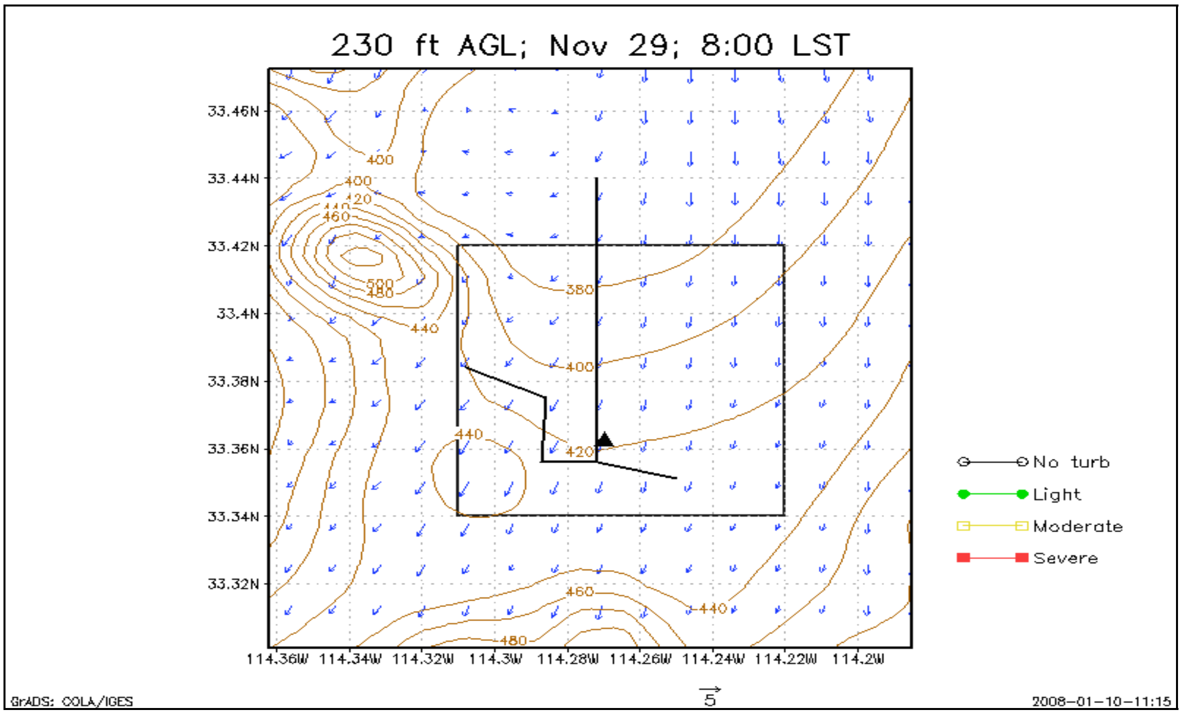

Figure 5. Wind (m/s) and turbulence forecasts at 1500 UTC 29 Nov. 2007 over YPG. Height contours are displayed in meters above mean sea level.

As can be seen in figure 5, the winds are light and from a northerly direction which is typical for the early morning hours in the region. No turbulence is forecasted on the grid area.

However, as the day progresses, more turbulence was forecasted, as seen in figure 6.

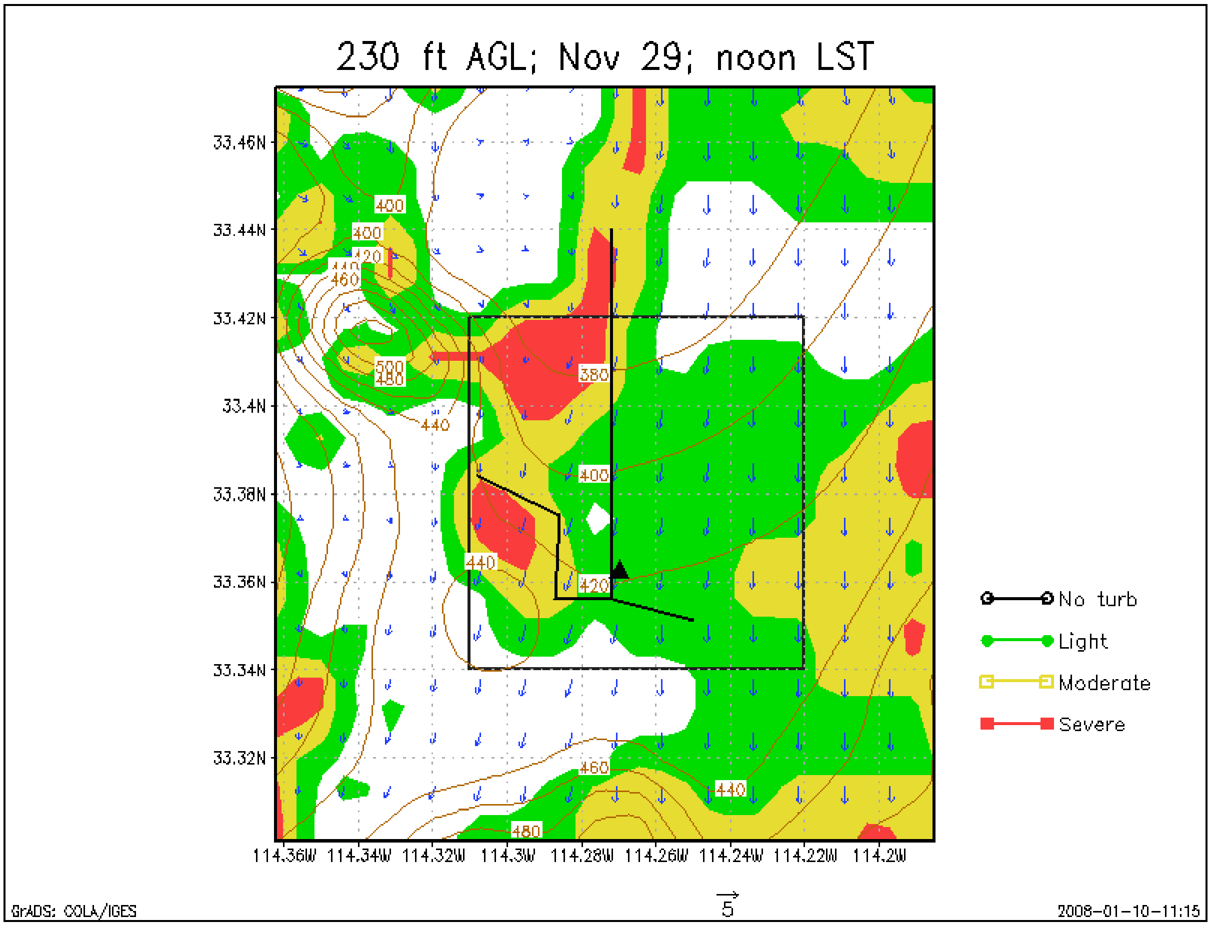

Figure 6. Wind (m/s) and turbulence forecasts at 1500 UTC on 29 Nov. 2007 over YPG. Height contours are displayed in meters MSL.

This trend for areas of MOD or SEV turbulence in small areas was prevalent each afternoon although wind speeds and any wind shear did not appear to increase significantly. After researching the problem, it became obvious that the height differences in the sigma levels were exceptionally small in the boundary and this led to significantly higher values of PI. The denominator in equation 1 became excessively large in the lowest four or five sigma levels due to the small values of ƏZ (change of height). This led to values of PI of over 1,000 in some cases when even values of 250 are often related to SEV turbulence.

The YPG studies did provide ARL an excellent opportunity to find flaws in the turbulence program that would not have been afforded otherwise since the increase in model vertical resolution provided a ground-breaking test for the software. Numerous changes in the software were made in early 2008 with an emphasis on providing a more accurate forecast for turbulence based on real-time PIREPs. In the lower levels, where the PI is used, and when the u and v component of the wind in the denominator of equation 1 are nearly identical, the differential can be very small, thus limits were set to prevent those terms from becoming too influential. When the differential between the grid points became smaller than 0.10, the limits were adjusted to

0.10 since these small differences are not significant in the production of turbulence anyway. Another change in equation was to change the exponential in the first term, the $(\text{windspeed})^2$ term, to 1.8 in an effort to reduce some of the bias in turbulence forecast based just on stronger low-level wind speeds. A final change was to adjust the categories that determine LGT, MOD, or SEV turbulence in an effort to reduce the excessive MOD and SEV turbulence forecasts.

In the higher levels the following changes and tests were made for the TI.

- The TI was adjusted to be parameterized based on the grid resolution. Cases were divided into two groups: one where the horizontal grid resolution was less than 8 km and one where it was greater than 8 km.
- An error in the differential mathematics was corrected.
- Tests were conducted with and without the convergence term. Results showed little change in the TI in both cases so it remains part of the TI.
- Tried to set limits of 0.10 as done with the PI, but this was an ineffective way of dealing with excessive turbulence forecasts and had little influence on the results because terms such as the stretching term or deformation term are often several orders of magnitude less than 0.10.
- For smaller grid sizes, less than 10 km, the categories for LGT, MOD, and SEV turbulence were adjusted to remove the bias of MOD and SEV turbulence.
- Some checks were added to the software to look for excessive turbulence forecasts, especially in the area of 4,000 to 8,000 ft AGL. In addition, changes were made in the layers above 8,000 ft AGL to remove biases.

These changes in the turbulence software can be seen in figure 7. Comparing figure 7 with figure 3 shows a vast reduction in forecasted turbulence at the same time and same level. Given the 2-km horizontal grid resolution, it is assumed that parameterizing the turbulence helped reduce the severe turbulence noted on figure 3. Additionally, the rule checks may have reduced the turbulence to levels being reported by pilots.

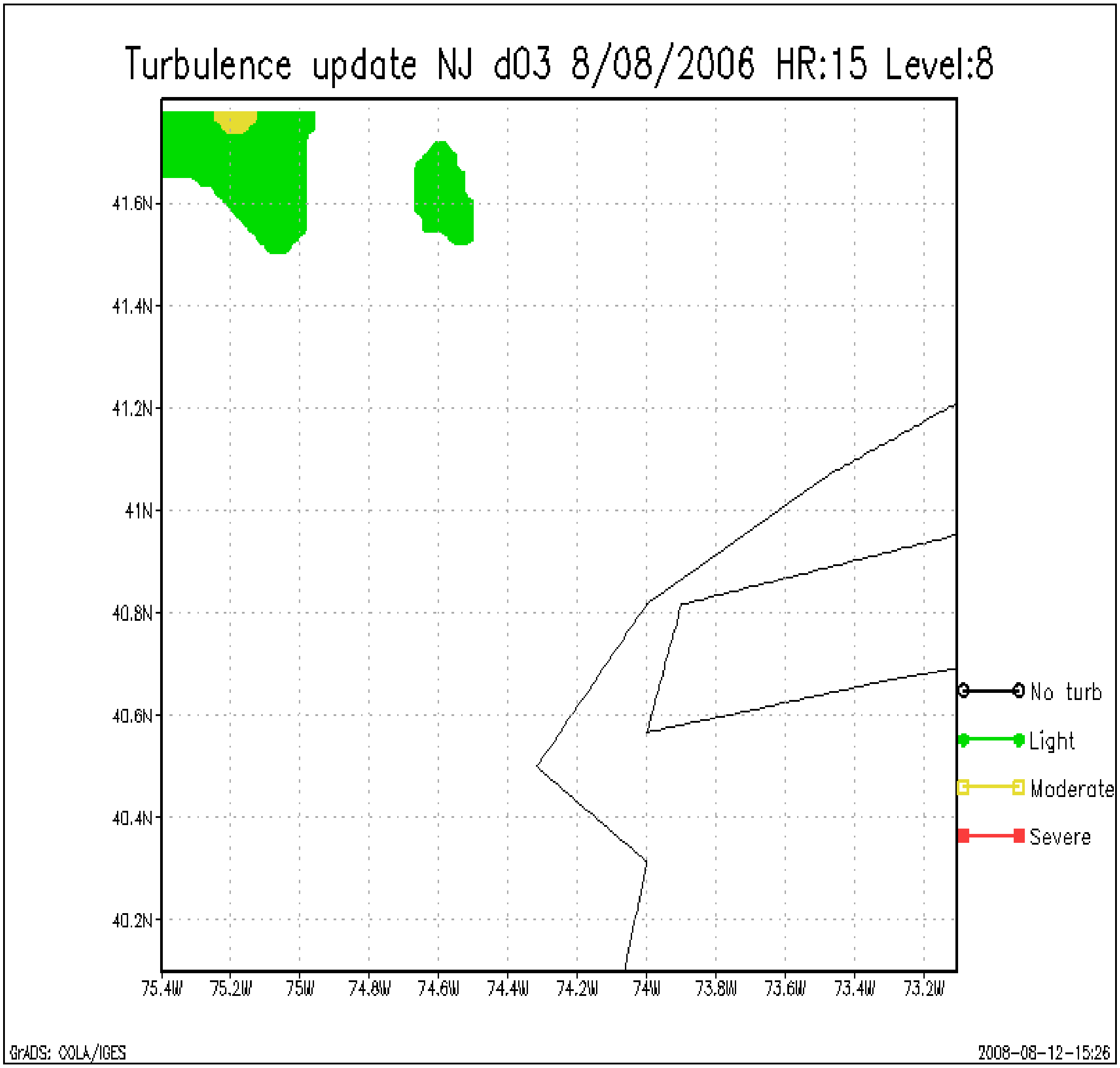

Figure 7. Updated turbulence forecast at 1500 UTC 08 Aug. 2006 using 2-km WRF output at 4,000 ft AGL.

It is uncertain how effective the changes in the low-level and higher-level turbulence routines are given the limited set of evaluated model runs so far. Additional testing and comparison to PIREPs will give more detailed information about improvements made in turbulence forecasting as mesoscale models trend to smaller grid sizes and additional sigma levels to provide more detailed model forecasts. It is apparent that the empirical routines formulated for predicting turbulence at higher levels and larger grid sizes may not capture the true nature of turbulence in the atmosphere. Ongoing efforts to understand and forecast turbulence at very small scales are still being developed and will undoubtedly add insight in solving this problem. For now, the best approach is to adjust what does exist and find a fit that provides the best results and skill for pilot and aircraft.

5. Conclusions

ARL, with an interest in high resolution mesoscale models for applications in the battlefield, has developed a forecast method to predict turbulence designed for a larger scale, but that also was tested for 2- and 1-km output of the WRF-ARW. While it is understandable that capturing clear-air turbulence is very difficult given the timescale and resolution involved, it still remains a goal to give a wide-ranging calculation of turbulence given the larger-scale conditions of the atmosphere. Verification was completed over a grid centered on northeast New Jersey since it contains a large number of airports and aviation traffic. Using a combination of the PI in the lower atmosphere and the TI in higher layers, comparisons were done for 18- and 2-km output from the WRF. While the WRF output did not show much difference between these two grids, there was a trend for more frequent turbulence forecasts and stronger intensities at the smaller horizontal grid sizes. It was also noted that errors were more common using the TI than the PI with a higher FAR and stronger bias to overforecast turbulence.

It was determined that turbulence, due to its variable time and space scales, needed to be parameterized to prevent excessive amounts and intensity at the smaller grids. It was also found that increasing the number of layers in the vertical in the WRF created additional forecasting problems near the surface.

Recent upgrades in the turbulence software included a parameterization based on grid resolution, limits to the PI to prevent excessive turbulence, slight adjustment to turbulence categories, and checks for illogical results based on the given data. These changes do show a decline in the forecasted turbulence and the intensity of the turbulence. More formal testing of these changes needs to conducted and will be using the latest upgraded WRF versions.

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Acronyms

AGL	above ground level
ARL	U.S. Army Research Laboratory
CAT	clear-air turbulence
CDW	Caldwell, NJ, airport
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
CVG	convergence
DEF	deformation
FAR	False Alarm Rate
FNMOC	U.S. Navy Fleet Numerical Meteorological and Oceanography Center
GRADS	Grid Application Development Software Project
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulations
JIEDDO	Joint Improvised Explosive Device Defeat Organization
KOKX	Upton, NY, airport
LGT	light
MOD	moderate
MM5	Mesoscale Model Version 5
PI	Panofsky Index
PIREPs	pilot reports
POD	Probability of Detection
RI	Richardson number
RIcrit	critical Richardson number
RRTM	Rapid Radiative Transfer Model
SEV	severe
TI	Turbulence Index

TSS	True Skill Score
UAS	Unmanned Aerial System
UTC	universal time coordinates
VWS	vertical wind shear
WRE-N	Weather Running Estimate-Nowcast
WRF	Weather Research and Forecasting model
WRF-ARW	Advanced Research version of the Weather Research and Forecasting model
YPG	Yuma Proving Ground

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